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Implications of the blockchain technology adoption by additive symbiotic networks

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ABSTRACT

A vibrant debate has been initiated around the potential adoption of blockchain technology for enhancing the development of industrial symbiosis networks, particularly for promoting the creation of additive symbiotic networks. Despite the potential benefits of trust creation and elimination of intermediary entities, adopting such innovative technologies promises to disrupt the current supply chains of those symbiotic networks. The literature on these topics is still beginning; thus, the present research intends to contribute. A framework for understanding the implications of adopting the blockchain technology in the supply chain structure (specifically, in the dependency dimension) of an additive symbiotic network was developed, considering a network theory lens. The case study method was deemed to be suitable for carrying out this research. A case study related to an additive symbiotic network is described in detail, with the development of two scenarios: scenario I "as-is" for the current state of the network and scenario II "to-be" considering the adoption of the blockchain technology. Results show that adopting blockchain technology impacts the supply chain structure of additive symbiotic networks. More specifically, there are implications for the power distribution among the network's stakeholders.

1. Introduction

Industrial symbiosis aims to achieve a mutually beneficial relationship between industries that intend to accomplish a productive use of by-products and wastes (Chopra & Khanna, 2014), allowing companies to produce more while spending fewer resources or energy through collaboration and cooperation (Neves et al., 2020). To Mirata & Emtairah (2005), industrial symbiosis programmes aim to create and develop industrial symbiosis networks that seek to respond to environmental concerns using (but not restricted to) spatial proximity. Digital transformation has been recognized as effective in the presentation of services, production of goods, business models, among others (Ronaghi & Mosakhani, 2022) and several studies have already started to show the potential of using innovative technologies from industry 4.0 to enhance the creation of industrial symbiosis networks. For example, Ferreira et al. (2021) demonstrated how additive manufacturing could promote waste valorization in an industrial symbiosis setting. Additive manufacturing and its distributed manufacturing capabilities are becoming a necessary process that can play a relevant role in transitioning from a linear to a circular economy (Cruz Sanchez et al., 2020). Given its potential to promote sustainable concepts through repairing and remanufacturing activities and reduction in the production of waste (Kravchenko et al. 2020), additive manufacturing is seen as an enabler for circular economy strategies toward sustainability, including the development of industrial symbiosis networks in this context. There are already examples in the literature of studies and projects demonstrating the potential of using recycled materials as material inputs for additive manufacturing processes (Ferreira et al., 2021; Sauerwein et al., 2019; Sauerwein & Doubrovski, 2018). We extend the use of additive manufacturing technologies as an enabler of industrial symbiosis networks where wastes and by-products from different industries can be used as material inputs in additive manufacturing processes. This paper designates these networks as "additive symbiotic networks" (Ferreira et al., 2022).

On the other hand, Tseng et al. (2018) highlighted that the use of data-driven analysis might potentially contribute to optimising sustainable solutions. In this sense, blockchain technology is seen as a tool that can be adopted to promote industrial symbiosis networks (Gonçalves et al., 2022). According to Kouhizadeh et al. (2019), blockchain technology allows to record information (representing contracts,

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Table 1
Blockchain's main characteristics and challenges. Retrieved from Schmidt & Wagner (2019).

Advantages	**Immutable**	Transactions on the blockchain cannot be tampered with once they are validated by the network.
	Trust	Transactions can be conducted without personal trust between parties, as blockchain provides consensus mechanisms to establish a valid state of truth.
	Transparent	Every participant on the network (in a permissionless setting) can access and view all previous transactions.
	Permanent	Blockchain always holds the entire transaction history. Every transaction that is verified is always retraceable.
Challenges	**Data quality**	Blockchain is mainly a database, and its value is dependent on the quality of input data.
	Network effect	Blockchain only creates value for participants given sufficient diffusion of the technology.
	Privacy	Blockchain requires every participant to share information within a transaction, even in private configurations.
	Uncertainty	The technological uncertainty is still high and the technology has not reached a mature state yet.

transactions, identities, assets or anything that can be expressed in digital form (Mandolla et al., 2019) across decentralized ledgers that are visible to all the entities involved in a network. There is currently work and research on applying blockchain technology to enhance an industrial symbiosis network setting, as seen in Gonçalves et al. (2022) and Ponis (2021). However, the existent literature regarding the adoption of blockchain technology in additive symbiotic networks is still scarce, with few studies examining the synergies between additive manufacturing technologies and blockchain technology (Ferreira et al., 2022; Kurpjuweit et al., 2019; Tseng et al., 2018) and this corresponds to the first research gap that this research intends to address.

Furthermore, considering that the development of additive symbiotic networks involves several independent companies or organizations that exchange material flows, money, and informational flows, according to Karuppiah et al. (2021), this is manifested through a supply chain, which is a network of sectors where material flows, money and informational flows occur. In additive symbiotic networks, inter-organizational relationships are established through synergistic transactions that include different sellers and buyers with geographically distant customer locations (Karuppiah et al., 2021). In this sense, it has been argued that adopting new technologies, such as blockchain technology, may substantially affect supply chain management, governance structures, and relationships (Oh et al., 2022; Durach et al., 2021; Treiblmaier, 2018). According to Awaysheh & Klassen (2010), three main dimensions that relate to the supply chain structure have been identified as having an important impact in addressing social and economic issues with the different supply chain members: dependency, distance and transparency. This paper focuses on the first one – dependency. Dependency is defined as the degree to which organizations rely on other supply chain members for critical resources, capabilities and components (Awaysheh & Klassen (2010)). Even though the blockchain has increasing potential to change supply chains structures (Karuppiah et al., 2021), according to Oh et al. (2022), successful examples of blockchain technology applications in supply chains are scarce and, moreover, the literature regarding the changes that may occur in the supply chain structure of an additive symbiotic network with the adoption of this innovative and disruptive technology are still in its very beginnings. Thus, this research also intends to address this second research gap.

From a network theory perspective, this study deals with implications that may occur within the structure of a supply chain, more specifically in the dependency dimension. The main aim is to understand the implications in the supply chain's structure of an additive symbiotic network, with the adoption of blockchain technology, more specifically in the relationships (strength) between the network stakeholders. For that purpose, three main research objectives seek to be achieved: i) to characterize the flows exchanged among stakeholders in an additive symbiotic network before the adoption of the blockchain technology; ii) to characterize the flows exchanged among stakeholders in an additive symbiotic network after the adoption of the blockchain technology and iii) to understand the strength of the relationships in the supply chain of an additive symbiotic network with the adoption of the blockchain technology. A case study representative of an additive symbiotic network in which additive manufacturing technology is used to produce recycled filament from plastic waste streams was developed to carry out this research. This case study deals with Polyethylene Terephthalate (PET) material which is the material used to produce plastic bottles. The PET bottles are the waste stream used as material input for an additive manufacturing process. When considering this symbiotic network, the unit of analysis within this case study corresponds to the supply chain of the additive symbiotic network itself. Two research phases were conducted with two different scenarios being developed and analysed: phase 1) "as-is" scenario – with the current map of the additive symbiotic network and phase 2) "to-be" scenario – a scenario drawn considering the adoption of the blockchain technology.

This paper has the following structure: after this introductory section, section 2 contains the theoretical background regarding the main concepts of this research, namely industrial symbiosis networks and additive symbiotic networks, the network theory and blockchain technology and its application in the supply chain management research field. Section 3 follows with the materials and methods, namely, developing a case study representing an additive symbiotic network. Section 4 presents the main results and discussion. Lastly, conclusions are presented in section 5.

2. Background

2.1. Additive symbiotic networks

The amount of waste and emissions generated worldwide has forced industries to adopt circular economy principles (Demartini et al., 2022; Khan & Ali, 2022). Chertow (2000) defined industrial symbiosis as "engaging traditionally separate entities in a collective approach to competitive advantage involving a physical exchange of energy, materials, by-products and water". Industrial symbiosis is considered to be a key strategy for the implementation of circular economic systems (Fraccascia et al., 2021) and mainly focuses on the concept of getting and sharing value from waste (Demartini et al., 2022). It is recognized as increasing the economic performance of businesses, creating more value for the entities involved, reducing energy and material losses, fostering eco-innovation, and improving the industrial processes' ecological footprints (Mortensen & Kørnøv, 2019). Industrial symbiosis can contribute to achieving certain sustainable goals (Liu et al., 2022) and is mainly concerned with the cyclical flow of resources across networks of companies, focusing on ways that lead to the optimization of resources based on the collaboration between different activities and industries (Domenech & Davies, 2011). The exchange of resources that occurs between the various entities that are also designated by stakeholders creates inter-organisational networks that are called ISNs. These resources correspond, among others, to energy, information and materials (Ferreira et al., 2019). Mirata & Emtairah (2005) defined ISNs as "a collection of long-term, symbiotic relationships between and among regional activities that involve physical or material exchanges and exchange of knowledge, technical and human resources, energy carriers, concurrently providing environmental and competitive benefits".

Angioletti et al. (2016) stressed out that there are a number of technologies considered important enablers for relevant changes in economies and society, highlighting the role of additive manufacturing

Table 2
Potential use of the blockchain technology within the supply chain management research area in an additive symbiotic network context. Retrieved from Cole et al. (2019).

Potential uses of blockchain technology within Operations and Supply Chain Management	Explanation
To improve and automate contracts **To reduce the need to develop trustworthy supply chain relationships.**	Blockchain is an emerging technology that is based on transactional and decentralized data sharing across a network that does not need trusted participants. The complexity of manufacturing ecosystems requires the development of new ways of trust through the blockchain technology and smart contracts.
To reduce the need for intermediaries and consequently reducing the complexity of the supply chain.	With the smart contracts performing reliably their role, international procurement organisations will no longer be needed.
To reduce the costs of transactions through automation, enabling real time auditing via timestamping.	The costs of many transactions have been lowered with digitisation. The blockchain technology introduction supports digitisation through costless verification.
To enhance product safety and security	Through the application of blockchain and smart contracts that provide records of testing, the security of the whole supply chain can be enhanced.
To enhance quality management by providing accessible information about batches	Paper-based freight documents are tampering, prone to loss and fraud. The blockchain can provide visible and easily accessible information about batches, improving service and aiding recalls.
To reduce illegal counterfeiting	The blockchain technology can provide information of the origin of a product, strengthening the transparency and traceability of goods in a supply network.
Improve inventory management	With the use of smart contracts, inventory management challenges can be overcome.
To accelerate work on design and new product development	The blockchain technology has allowed the development of new insurance products, improving efficiency and delivering greater transparency between teams.
To revolutionise the Internet-of-Things in Operations Management	Blockchains provide the basis for an open manufacturing systems that shares data with its customers, as well as knowledge on how to handle the data that is shared with other organizations involved in the supply chain.

that practitioners and researchers have seen as one of these key technologies. Aligned with the circular economy, additive manufacturing is seen as promising for a more sustainable production that enables the demand production of spare parts for repair or avoids material losses compared to other traditional technologies (Sauerwein et al., 2019). According to Angioletti et al. (2016), additive manufacturing technology allows a good integration between the circular economy approach and the technology itself due to the opportunities that can be increased through the value chain, such as: a reduction of the amount of material used from maintenance to reuse and from the rework to recycling and a reduction in the energy consumption. This additive technology enables circular production systems, contributing to the development of circular strategies, including industrial symbiosis's strategy that aims to achieve more sustainable production.

According to Ford & Despeisse (2016), a diversity of materials can be used for additive manufacturing depending on the type of additive manufacturing process that is going to be used. This includes polymers, ceramics, metals, and sometimes composites. For example, Reich et al. (2019) investigated the environmental impact of polymer recycling in their study, stressing out many types of waste polymers that have been recycled into 3D printing filament, such as polylactic acid, acrylonitrile butadiene styrene, polyethene terephthalate or sometimes composites using carbon-reinforced plastic. When operating a 3D printer through extrusion, the filament itself is used (Kreiger et al., 2013). However, Reich et al. (2019) highlighted that it is possible to eliminate the need for filament completely and print directly from pellets, particles, flakes, shreds, or recycled plastic through fused granular fabrication or fused particle fabrication. The idea of recycling plastic is not new; plastics are considered the vastest materials in the industrial environment, and recycling has been established as the ideal post-consumer treatment of plastic waste (Alexandre et al., 2020). Over the recent years, material extrusion 3D printers that can print directly from plastic pellets have been developed (for example, GigabotX, Cheetah Pro, David), allowing the fabrication of 3D printed materials or products from recycled plastic materials (Alexandre et al., 2020). This shows that additive manufacturing enables systems to recycle and reclaim waste material as material input for productive processes (Peeters et al., 2019), creating an environment favourable for developing industrial symbiosis networks. Despite its potential, there is still a lack of research relating the additive manufacturing and industrial symbiosis networks (Ferreira et al., 2021).

Industrial symbiosis relationships are fostered through a different number of factors that include (Neves et al., 2020): to obtain economic advantages, meet environmental requirements such as the reduction of greenhouse gas emissions, save resources, protect the exploitation of natural resources and reduce the waste that would be otherwise sent to an incinerator or landfill. By creating a collaborative web of material, knowledge and energy exchanges between different organizational units, the main aim of industrial symbiosis networks is to reduce the production of waste by the industrial sector and reduce the intake of virgin raw materials (Domenech & Davies, 2011). Authors as Mirata & Emtairah (2005) highlighted the potential benefits of developing industrial symbiosis networks such as:

Economic benefits that emerge from a reduction in costs related to waste management, resources inputs in production and from generating extra income due to higher values of waste streams and by-products.

Business benefits that are connected to the improvement of relationships with external parties, new markets and products and the development of a green image.

Social benefits due to the generation of more employment and improving the quality of the existing jobs through the creation of a safer, natural, and cleaner working environment.

Environmental benefits arise with the improvement in the use of resources, reduction of pollutant emissions, and reduction in non-renewable resources.

It is expected that the additive symbiotic networks, through their higher level of collaboration and connectivity, have the same benefits as highlighted in the studies mentioned above for industrial symbiosis networks.

2.2 The blockchain technology.

Table 3
Framework developed by Treiblmaier (2018) applied to blockchain-based supply chain management research.

Characteristics of the Network Theory	Blockchain-based networks
Behavioural assumptions	Interorganizational trust, information sharing
Problem orientation	Design of transactions and communication
Key questions	To what extent does the blockchain replace personal trust?
Primary focus of analysis	Relationships within the network
Nature of relations	Contractual relations, personal relations
Primary domain of interest	Mutual adaption of relations through the blockchain technology

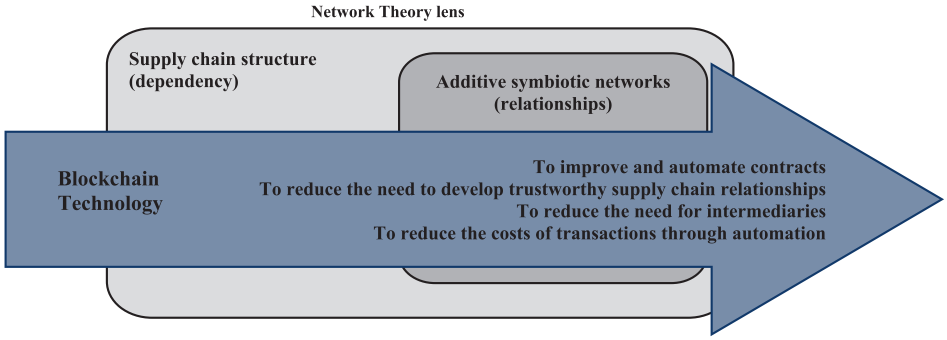

Fig. 1. Advantages of using the blockchain technology from a supply chain management perspective of an additive symbiotic network.

Over the last years, blockchain technology has gained substantial awareness and hype as a disruptive technology with several promising benefits that include improved traceability and transparency, cost savings and enhanced sustainability (Kouhizadeh et al., 2021). Golosova & Romanovs (2018) describe the blockchain as an incorruptible digital ledger where economic transactions can be coded to record more than just financial transactions but also virtually everything that has value. A blockchain holds a unique record of the data stored in blocks within each participant's node (Blossey et al., 2019). Each block corresponds to tamper-resistant records and evident digital ledgers that are usually implemented without a central authority and in a distributed fashion (Yaga et al., 2018). A single transaction involving one or more entities is the basic unit of a blockchain. This could correspond to a transfer of information, or it can correspond to a payment process. A cryptographic hash is used to generate transaction hashes that encrypt the content of these transactions (Treiblmaier, 2018).

Cole et al. (2019) highlighted that a blockchain has four critical characteristics that stands-up, namely: i) it is designed to be synchronised and distributed across networks, encouraging companies and businesses to share data; ii) the smart contracts, which are one of blockchain's applications, representing an agreement between entities in the blockchain; they can also define conditions and functions, that may include the validation of assets in a variety of transactions with and without monetary elements; iii) the blockchain is built based on peer-to-peer networks in which there must be an agreement between all the relevant parties for a transaction to be valid, and this helps to keep potentially fraudulent transactions excluded from the database and iv) immutability that means that the transactions that occur within the network are recorded on the database and cannot be altered. In their study, Schmidt & Wagner (2019) emphasized the blockchain's main advantages and challenges (Table 1). It is evident that, on the one hand, blockchain not only enables transactions to occur in specific conditions where there is no necessity for personal trust among the parties, but it is also a permanent database that promotes transparency. On the other hand, there are significant challenges that concern it, such as information sharing on transactions required for all entities.

Blockchain has several applications that are built for a specific function or purpose. Examples include smart contracts and distributed ledger systems between businesses and cryptocurrencies (Yaga et al., 2018). The adoption of blockchain technology and some of its applications can replace intermediaries with non-value-adding and aid intermediaries at complex points to improve transparency and promote trust in the service that is being provided (Durach et al., 2021). Within its several applications, the blockchain supports the smart contract concept. A smart contract is a "*computerized transaction protocol that executes the terms of a contract*" (Szabo, 1997). According to Schmidt & Wagner (2019), this means that the contract is automatically executed when the blockchain achieves a pre-specified state. Since smart contracts are entities within the distributed network, (theoretically) there is no longer a need for a trusted authority to execute the contract. These agreements exist in the blockchain platform as a software code which guarantees their self-executive nature or autonomy based on predefined specifications or rules (Treiblmaier, 2018). To Ronaghi & Mosakhani (2022), implementing blockchain technology is expected to be effective in areas related to business ethics, to monitor corporate governance, and to achieve sustainability.

In fact, there are several potential benefits in adopting blockchain technology for promoting the development of the concept of industrial symbiosis, particularly for the development of additive symbiotic networks (Ferreira et al., 2022). With the adoption of blockchain technology, companies can ensure a secure and transparent process of transactions (Rehman Khan et al., 2022) and furthermore, blockchain

Fig. 2. Bottle PET Filament. Retrieved from: B-PET (2021).

Table 4
Stakeholders' description.

Stakeholders	Description	Activity
INTI	National Institute of Industrial Technology in Argentina	Conduces scientific research and technical tests
Enye Technologies	Deign, technology and ideation company	Innovative hub that creates and funds start-ups and spin-offs
B-PET	Company that sells 3D printing technologies and services	3D printing technologies and services
Funding entity	Public funding	Gives funds to invest in 3D printing equipment and services
Intermediary entity	Consulting group	Helps to get the public funding
Cooperative Correcaminos	Local cooperative in Argentina that collects and recycles solid and inorganic residues such as metals, plastics, and paper.	Local cooperative that collects, separates, and manages waste
ANMAT	National Administration of Medicines, Food and Medical Technology in Argentina that assures that all health products are safe and of quality.	Agency that approves companies to produce food grade PET pellets from post-consumer waste streams
ALPEK (formally ECOPEK)	A global integrated polyester-based business unit, leader in the production of PET resins and PET recycling.	Recycler company that transforms PET waste streams into PET pellets or flakes
Prosumers	Cooperative Correcaminos	Cooperatives that use the recycled filament and the 3D printing equipment for their own needs
3D Printing Services Companies	Multiple companies that use or sell 3D printing technology and equipment	Companies that use the recycled filament to personalized and customized products and services
Final consumers	Multiple companies or individual consumers	Consumers that aim to buy and use 3D printed products

technology features' have been claimed by scholars to have enormous potential to facilitate transformation within multiple industries and to disrupt transaction approaches (Ning & Yuan, 2021). Blockchain technology can provide the necessary infrastructure for companies and clients to conduct online transactions without the typical need for an intermediary entity (which is commonly used to guarantee security) and, consequently, reduce the costs associated with transactions (Durach et al., 2021). However, despite of its benefits, adopting blockchain technology within an additive symbiotic setting remains to be further explored in the literature (Gonçalves et al., 2022).

Blossey et al. (2019) argued that blockchains constitute decentralized autonomous and collaborative organizations for value exchange and creation. Information sharing connects dispersed entities, which facilitates improving relationships within supply chains, reduces risks and costs, and prevents falsification and fraud (Kouhizadeh et al., 2019). Furthermore, Rehman Khan et al. (2022) highlighted that with the adoption of blockchain technology, companies can improve efficiency and reduce the overall costs through regenerating resources. Adopting new technologies, such as blockchain technology, has great potential to transform supply chains (Karuppiah et al., 2021) and may have substantial implications within the supply chain of additive symbiotic networks.

2.2. The implications of blockchain technology in the supply chain of additive symbiotic networks

Due to their higher level of collaboration and connectivity, the additive symbiotic networks require supply chains to expand their traditional relationships to a more collaborative effort (Herczeg, 2016). The additive symbiotic networks involve inter-organizational relationships that are manifest through interactive activities, specifically, we focus on the waste exchange in this research. This waste exchange between different companies creates an interdependency because organizations cannot control all the resources needed for their main activities (Herczeg, 2016). It is managed cooperatively, with different strategic alliances (Boons & Baas, 1997).

Blockchain technology can be adopted to improve the process of industrial symbiosis between different organizations (Gonçalves et al. (2022); Ponis (2021)) and, consequently, enhance the development of additive symbiotic networks. One of the blockchain applications is smart contracts that can potentially decrease the impact of bounded rationality within a transaction. Bounded rationality is emphasized by Momo et al. (2021) as a human condition that relates to limitations in the cognitive domain and, when considered within a transaction context between different organizations, does not allow to predict all types of situations that can affect the contract among the organizations. However, by creating a more reliable way of transaction, Cole et al. (2019) highlighted that blockchain technology can significantly reduce the need for an intermediary entity, potentially removing the middleman and creating an even more transparent and agile supply chain. Additionally, blockchain technology offers an immutable and permanent database where information is shared efficiently without the need for a long-term relationship (Schmidt & Wagner, 2019).

Improvements, especially in digital technologies, may have impacts on supply chain management and logistics (Balouei Jamkhaneh et al., 2022) and, according to Treiblmaier (2018), with the adoption of blockchain technology, the direct relationships within a network may still be maintained. Still, their strength might be affected, and also, the indirect relationships might be replaced by new direct ones. Thus, adopting blockchain technology in an additive symbiotic network is expected to have implications for its inherent supply chain. In the supply chain management field, the specific applications of blockchain technology include contract enforcement, record keeping and transaction functions (Ning & Yuan, 2021). Supply chain management involves designing, planning, executing and monitoring logistics processes. Lagorio et al. (2020) highlighted in their systematic literature review that innovative technologies, such as the blockchain, can support that distinct variety of activities. Furthermore, Cole et al. (2019) reveal several opportunities to study blockchain technology within the supply chain management field (Table 2).

Four theories within the supply chain management field can be used to explore the implications in the supply chain of a network with the adoption of blockchain technology (Halldorsson et al., 2007): transaction cost analysis (Halldorsson, 2002), the resource-based view (Miller & Ross, 2003), network theory (Gadde & Hakansson, 2001) and the principal-agent theory (Logan, 2000). According to Treiblmaier (2018), the transaction cost analysis and the principal agent theory are used to answer questions regarding how to structure or design a supply chain. The network theory and the resource-based view help answer questions regarding what is needed for managing those supply chain structures. In additive symbiotic networks, organizations exchange information, goods and services in a supply chain network, and thus, the relationship between the entities within the system is not always easy to understand (Queiroz & Fosso Wamba, 2019). Furthermore, to achieve the sustainable objectives of additive symbiotic networks and considering the proactive and collaborative effort surrounding them, there is a need to manage the relationships between the organizations involved in the networks (Boons & Baas (1997)). The network theory is linked to dyadic relationships and the networks where they are inherent and can be used to provide a basis for the conceptual analysis of reciprocity in cooperative relationships (Halldorsson et al. (2007)). According to Treiblmaier (2018), this theory evaluates connections and exchanges between organizations, focusing on managing relations rather than the transactions itself and its main objective is to explore the role and nature of interorganizational relationships and how they can be managed. When applied to the supply chain management field, it has been used to map actors, resources and activities in a supply chain (Halldorsson et al. (2007)). Hence, and considering the main goal of this study which is to

Table 5
Primary data collection.

Research phase	Objective	Data collection
Phase 1 "*as-is*" scenario	• Characterization of the case study Identification of resources exchanged and stakeholders Identification of the focal organization	• 2 Unstructured interview Questionnaire A
	• Identification and quantification of value flows	• 4 Unstructured interview Questionnaire B
Phase 2 "*to-be*" scenario"	• Identification of several applications of the blockchain technology within the additive symbiotic network	2 Unstructured interview
	• Identification and quantification of value flows after blockchain technology	• Questionnaire C

understand the implications in the supply chain's structure (relating to the dependency dimension) of an additive symbiotic network, namely in the relationships between the stakeholders in the network, the network theory was considered the most suitable to achieve this goal. Treiblmaier (2018) highlighted in his study how the different attributes of the blockchain technology can be incorporated within the network theory (Table 3).

Oh et al. (2022) emphasised that research employing qualitative methods is needed to explore the meaning of blockchain technology in the supply chain management domain and in the designing of processes of blockchain-technology-enabled supply chains. Furthermore, Kummer et al. (2020), in their systematic review of blockchain literature and supply chain management, highlighted that there are several studies already examining the adoption of blockchain technology using the network theory. However, the literature regarding the implications of adopting blockchain technology from a supply chain management perspective to enhance additive symbiotic networks remains to be further explored. Overall, the literature presented above suggests that there is a need to apply the network theory to understand the implications of adopting the blockchain technology in the supply chain structure of an additive symbiotic network, with these implications potentially linked to the relationships within the network, and potentially associated with the strength of their ties and embedded with other relationships (Queiroz & Fosso Wamba, 2019).

Therefore, within the scope of this research, a framework for understanding the implications of adopting blockchain technology in the supply chain structure of an additive symbiotic network was developed, considering a network theory lens (Fig. 1). Through this lens, the primary focus of analysis are the relationships within the supply chain of an additive symbiotic network, and the primary domain of interest is the mutual adaptation of the relationships with the adoption of blockchain technology (Treiblmaier, 2018). This framework considers that the relationships between the stakeholders of an additive symbiotic network are used as a proxy to assess the dependency dimension of the supply chain structure. Additionally, the framework highlights four supply chain management areas, previously identified by Cole et al. (2019) (Table 2), that relate to the supply chain structure, where the blockchain technology may be considered to bring value: i) improving and automating contracts, ii) reduce the need to develop trustworthy supply chain relationships, iii) reduce the need for intermediaries and consequently reducing the complexity of the supply chain, and iv) reduce the transactions cost through automation.

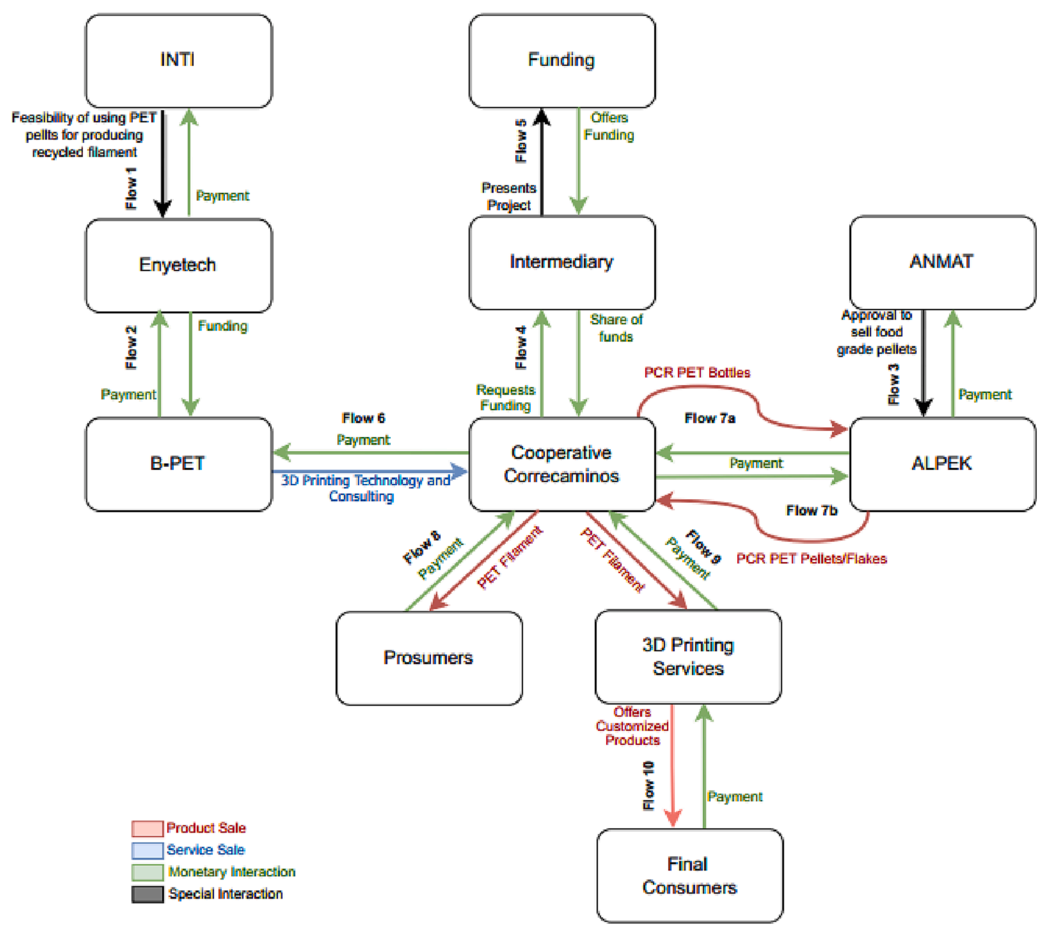

Fig. 3. Identification of the value flows exchanged between the stakeholders of the additive symbiotic network in scenario I.

Table 6
Value flow matrix for the additive symbiotic network in scenario I.

From: / To:	INTI	Enyetech	B-PET	Funding	Intermediary	Coop. Correcaminos	ANMAT	ALPEK	Prosumers	3D Printing services	Final consumers
INTI		Flow 1 – directResearch & Development (0.51)									
Enyetech	Flow 1 – reciprocalMoney (0.11)		Flow 2 – directFunding (0.96)								
B-PET		**Flow 2 – reciprocal**Money (0.01)				**Flow 6 – direct** 3D printing technology and consulting services (0.96)					
Funding					**Flow 5 – reciprocal**Funding (0.76)						
Intermediary				**Flow 5 – direct**Project Presentation (0.32)		**Flow 4 – direct**Funding Network (0.18)					
Cooperativa Correcaminos			**Flow 6 – reciprocal**Money (licence fee) (0.65)		**Flow 4 – reciprocal**Share of funding (0.54)			**Flows 7a and 7b – direct**Bales of PCR PET bottles (0.96) and money (0.22)	**Flow 8 – direct**3D printing filament (0.32)	**Flow 9 – direct**3D printing filament (0.11)	
ANMAT								**Flow 3 – direct**Approval to produce food grade pellets (0.76)			
ALPEK						**Flows 7a and 7b – reciprocal**Money (0.96) and PCR PET pellets or flakes (0.32)	**Flow 3 – reciprocal**Money (0.22)				
Prosumers						**Flow 8 – reciprocal**Money (0.54)					
3D Printing Services						**Flow 9 – reciprocal**Money (0.96)					**Flow 10 – direct**Customized products & services (0.76)
Final consumers										**Flow 10 – reciprocal**Money (0.96)	

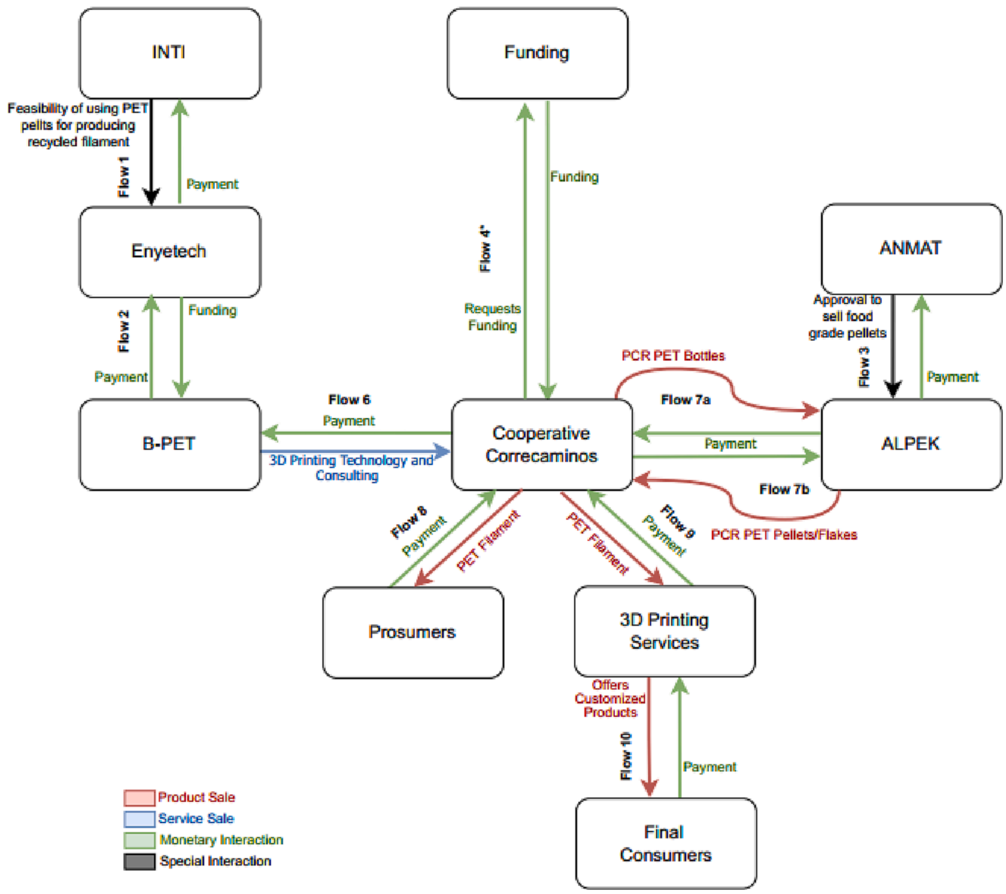

Fig. 4. Identification of the value flows exchanged between the stakeholders of the symbiotic network in scenario II.

3. Materials and methods

3.1. B-PET case study

According to Eisenhardt (1989), the case study is seen as a research method that concentrates on understanding the dynamics present in single settings, allowing a detailed empirical description of a specific phenomenon in which various sources of evidence are used (Yin, 2009). Case studies can be descriptive, exploratory or explanatory (Yin, 2009). Considering this is an exploratory investigation (i.e., additive symbiotic networks and blockchain technology), the case study approach is often considered the most suitable. Typically, case studies are used for exploratory research to understand in-depth a phenomenon in an early stage of an investigation that is not totally understood yet (Voss et al., 2002; Yin, 2009). Thus, similarly to successful single case study approaches performed by Ferreira et al. (2023) or Davies et al. (2022) or Naghshineh & Carvalho (2022), we have also chosen a single case study that may potentially be used as a pilot case in future studies involving multiple case study approach. This may result in a meaningful contribution to knowledge and theory building (Yin, 2014). Even though Eisenhardt (1989) and Yin (2009) advise the use of multiple case studies, Voss et al. (2002) highlighted that the fewer the cases, the greater the opportunity to have depth of observation. Consequently, a single case study representing an additive symbiotic network composed of companies that incorporated recycled materials in their activities or processes was considered pertinent for developing this research work.

Since this case study follows a qualitative positivism paradigm, taking Yin's (Yin, 2009) perspective of the case study approach, four quality criteria were considered to ensure the quality of the study, namely (Voss et al., 2002; Welch & Piekkari, 2017):

Construct validity: use of multiple sources of evidence – primary and secondary data were collected using different sources. After conducting the data analysis, a report was constructed, discussed, and validated with the focal company's expert.

Internal validity: explanation building – a critical analysis of the main findings and conclusions were presented to the expert involved in the study.

External validity: replication logic – the main goal of using this case study was not to generalise its results. Instead, it aimed to explore the application of a disruptive technology into news domains – the additive manufacturing context and the industrial symbiosis network setting. The unit of analysis for the case study was defined, and a case study context was given to support the results of similar cases.

Reliability: use of a case study protocol – for this case study, the protocol was created using an existing model from the literature. More specifically, the model developed by Ferreira et al. (2019) was employed for the mapping and analysis of an industrial symbiosis network.

There are numerous possibilities to valorize waste through additive manufacturing, evidencing the potential of developing additive symbiotic networks in this context. Ferreira et al. (2021) mention the possibility of using industrial 3D printers capable of fused particle fabrication directly from waste plastic streams (external wastes). Thus, 3D technology can be one of the solutions to mitigate the dumping of waste in landfills and respond to the increasing concerns of environmentalists, academics and local governments. When focusing on the municipality level, solid waste management is a complex problem, specifically in developing countries where it is typically inefficient due to the lack of proper financial and administrative structures, infrastructures, appropriate regulations, and adequate human resources (Botello-Álvarez et al., 2018). Waste pickers' importance and relevance to the solid waste management problem have been studied mainly in Asian and Brazilian countries. For example, Botello-Álvarez et al. (2018) highlight that

Table 7
Value flow matrix for the case study under investigation for scenario II.

From: To:	INTI	Enyetech	B-PET	Funding	Coop. Correcaminos	ANMAT	ALPEK	Prosumers	3D Printing services	**Final consumers**
INTI		**Flow 1 – direct**Research & Development (0.51)								
Enyetech	**Flow 1 – reciprocal**Money (0.11)		**Flow 2 – direct**Funding (0.96)							
B-PET		**Flow 2 – reciprocal**Money (0.01)			**Flow 5 – direct**3D printing technology and consulting services (0.96)					
Funding					**Flow 4 – Direct**Funding (0.96)					
Cooperativa Correcaminos			**Flow 5 – reciprocal**Money (licence fee) (0.65)	**Flow 4 – indirect**Money (fee) (0.18)			**Flows 6a and 6b – direct**Bales of PCR PET bottles (0.96) and money (0.22)	**Flow 7 – direct**3D printing filament (0.32)	**Flow 8 – direct**3D printing filament (0.11)	
ANMAT							**Flow 3 – direct**Approval to produce food grade pellets (0.76)			
ALPEK					**Flows 6a and 6b – reciprocal**Money (0.96) and PCR PET pellets or flakes (0.32)	**Flow 3 – reciprocal**Money (0.22)				
Prosumers					**Flow 7 – reciprocal**Money (0.54)					
3D Printing Services					**Flow 8 – reciprocal**Money (0.96)					**Flow 9 – direct**Customized products & services (0.76)
Final consumers									**Flow 9 – reciprocal**Money (0.96)	

Brazil is starting to recognize and formalize waste pickers' activities by creating urban cooperatives and public regulation of organized groups that perform selective collection, classification and commercialization of recyclables. Commonly in the large metropolis of the Global South, a few multinational corporations manage the collection and destination of urban garbage. However, since it is an expensive, time-consuming and bureaucratic process, only a few groups have achieved the formal status of a cooperative, and even a smaller group can have access to official microfinance and funding opportunities (Gutberlet, 2012).

An exploratory case study was carried out on an additive symbiotic network in which additive manufacturing technology is used to manufacture products from recycled filament used in 3D printers. In this case study, the additive manufacturing technology is provided by a 3D printing company that outsources production, provides start-up consulting services to manufacturers, provides commercial materials such as catalogues and branding, quality control criteria and procedures, and licences the product's name. The company under study is named B-PET (https://bpetfilament.com/), with its global headquarters in Buenos Aires, Argentina and its European headquarters in Valencia, Spain.

B-PET developed the process of waste recycling to incorporate it into 3D printing equipment, allowing the production of the first 3D printing filament made 100 % from recycled post-consumer PET bottles (Fig. 2). It is an engineering thermoplastic material mainly used for packaging purposes due to its excellent CO_2 and O_2 barrier and mechanical properties. In its amorphous phase, it's a colourless and crystal-clear material. B-PET effectively recycles PET waste streams into fully functional 3D printing materials through fused filament fabrication technology. In this case study, PET bottles appear in urban solid waste streams and are gathered by urban waste collectors that are concentrated within the Buenos Aires Metropolitan Area. These waste collectors are precariously organized in cooperatives that produce bales with a selection of green, blue and "crystal"- clear bottles. These bales are then dispatched to warehouses with a legal framework that can, in turn, sell the bales to one of the three authorized PET recyclers in Argentina that produce food-grade PET pellets from PET Post-Consumer Recycled (PCR) waste, mainly through mechanical extrusion processes. By combining adequate 3D technology, equipment, and services with PET pellets, it is possible to produce filament to be used in 3D printers. B-PET will continue developing new products through R&D and help build networks within local communities worldwide.

Therefore, this case study presents an additive symbiotic network formed from the PET bottles of the PCR waste streams. The relationships in the supply chain of that additive symbiotic network were considered the unit of analysis. Table 4 provides an overview of the case study's eleven stakeholders. Eight entities are enrolled in the additive symbiotic network, namely: i) INTI – the National Institute of Industrial Technology – an institute that conducts scientific research and technical tests; ii) Enye Technologies – an innovation hub that created B-PET; iii) B-PET – company that produces and sell 3D printing technology and services; iv) Funding entity – public funding to invest in 3D equipment and services; v) Intermediary entity – a consulting company that helps to get the funds from the public funding; vi) Cooperative Correcaminos – local cooperative that collects, separates and manages waste; vii) ANMAT – National Agency that approves companies to produce good grade PET pellets from PCR waste streams; viii) ALPEK – one of Argentina's PET recyclers for food-grade applications. Three additional groups of stakeholders are considered despite the fact they do not represent any specific entity: i) 3D printing services – multiple companies that use or sell 3D printing technology and equipment; ii) Final consumers – multiple companies or individual consumers that aim to use 3D printed products and iii) Prosumers – they represent the local cooperatives that can use the 3D printing material and equipment for their own or can sell it to others.

3.2. Data collection

To carry out this study, two research phases were considered:

Phase 1) "as-is" scenario I represents the current map of the additive symbiotic network. In this research phase, data regarding the network's stakeholders and resources exchanged among them was collected to create a value flow matrix to characterize the main flows and stakeholders of an additive symbiotic network (before blockchain technology). This research phase intends to achieve the first research objective: to characterize the flows exchanged among stakeholders in an additive symbiotic network before adopting blockchain technology.

Phase 2) "to-be" scenario II – this scenario was drawn considering the adoption of blockchain technology. It is a conceptual scenario developed by the research team. In this phase, data regarding the potential applications of using blockchain technology within the supply chain of an additive symbiotic network were collected. Additionally, data relating to the stakeholders and flows exchanged between them in the network was collected to create a new value flow matrix compared with the previous scenario I. The aim was to characterize the flows exchanged among stakeholders in the network after adopting the blockchain technology and to understand the strength of the relationships in the supply chain of an additive symbiotic network in this new setting - allowing to achieve the second and third research objectives.

For this case study, primary and secondary data were collected using different sources and methods. The primary data collection (Table 5) was performed through unstructured interviewers and questionnaires with an expert belonging to the focal organization of the network. The expert corresponded to the technical advisor to the leadership team with more than 15 years of experience. The interviews aimed to collect data for both research phases regarding the additive symbiotic network, its stakeholders, and resources exchanged and to discuss and validate the study's main conclusions. In addition to the primary data collection, secondary data from the website news of B-PET (https://bpetfilament.com) was collected.

In the first research phase, questionnaire A was developed to understand the main resources exchanged and the main stakeholders in the network. After, questionnaire B was created to quantify the value flows within the network. In the second research phase, questionnaire C was developed to understand the changes that could occur in quantifying each value flow after adopting blockchain technology. The three questionnaires are available in the supplementary information file (Appendix A).

Mapping the value network of the case study – scenario I – "as-is".

The three-step method used by Ferreira et al. (2019) for mapping and analysing an industrial symbiosis network is applied in this study, and the criteria developed by Hein et al. (2017) to quantify each value flow within the network. The methodology and aggregate scores created by Feng (2013) were used to assess the power distribution among the different stakeholders. The following sub-sections map the current status of the network "*as-is*" – representing scenario I.

3.2.1. Identification of the stakeholders

The first step is to identify the symbiotic network's focal organization and main stakeholders, considering Table 4. The focal organization is responsible for conducting all the investigations and negotiations needed and regulates the symbiotic network's operationalization and maintenance. For this case study, the B-PET company was responsible for producing and making available the 3D printing technology necessary to incorporate PCR waste streams into filament for 3D printing. B-PET was the entity responsible for providing the means to conduct all the research, studies, and tests for the development of the bottles' PET filament. Thus, B-PET was considered in this study as the focal organization.

As in an industrial symbiosis network, an additive symbiotic network is constituted by different entities that exchange resources among them, designated by stakeholders. The stakeholders differ from themselves in two ways: the indirect partners (that involve an indirect but necessary type of collaboration that support the exchange of resources) and the direct partners (involving the directly engaged stakeholders in the exchanges). Through Questionnaire A and unstructured interviews with the focal organization, it was possible to identify the different stakeholders of the network and their contribution to the symbiosis process.

Thus, the indirect partners for this case study are:

- **INTI** - INTI conducted the preliminary product development and validation. The company Enye Technologies has paid for several scientific research and technical tests and reports provided by INTI to demonstrate the feasibility of using PET pellets from PCR waste streams to produce filament for 3D printing.
- **Enyetech** – the company is an innovation hub that first came up with the concept of using waste streams to produce filament for 3D printing. The company has also patented this process. After that, they created B- PET LLC, an independent spin-off company, to develop this business.
- **ANMAT** - Currently, only companies with the national agency ANMAT's approval can produce food-grade PET pellets from the PCR waste stream. Therefore, the approval of these entities is critical in this process.
- **Funding** – public funding is a way for the local cooperatives to get funds to invest in 3D equipment and services through the help of an intermediary stakeholder. The public funding gives funding to both local cooperatives and possible intermediaries.
- Additionally, the direct partners were considered:
- **Cooperative Correcaminos** – a local cooperative with two warehouses where they collect, separate and manage waste from different materials. The local cooperatives are responsible for collecting and gathering the waste streams and selling them in bales to PET recyclers in Argentina. In return, they received the PET pellets or flakes ready to be used in the 3D printers to produce filament. Currently, these cooperatives are showing interest in acquiring a licence from B-PET LLC to manufacture B-PET filament products that they can use in two types of ways: As prosumers - the cooperative has the material (the recycled filament) and the equipment and can use it for their own benefit or can sell it (e.g. for schools). To 3D printing services companies – the cooperative sells the service to the market, which aims to satisfy the End consumers' needs. Typically, cooperatives buy raw materials from B-PET-certified suppliers and sell final products to individual, corporate or government consumers. B-PET provides all technical know-how during the production line setup and quality control processes. B-PET also provides marketing support with Technical Data Sheets, Safety Data Sheets, and other commercial materials, namely the brand's logo, name and sales channels.
- **ALPEK** - to effectively recycled PET to be used in 3D printing, it is necessary that PET bottles from post-consumer streams are presented in the form of flakes or pellets. ALPEK is a global polyester producer and recycler and is one of Argentina's approved PET recyclers for food-grade applications. Within this additive symbiotic network, this company is responsible for selling PET pellets or flakes to local cooperatives.

Intermediary – for this type of symbiotic network, there is a need to have an intermediary between the local cooperatives and ALPEK or the public funding entities. Since the local cooperatives do not have the necessary means to get invoices for the waste streams they sell to ALEPK, they need an intermediary entity. The local cooperatives, therefore, give to the intermediary information about the wastes that they are sending to the recycler, and in exchange, the intermediary provides money to the local cooperative that they received from selling the waste streams to the recycler. The intermediary passes information to the recycler about the waste streams and data for the invoices. However, in this case, study and considering that the cooperative Correcaminos has already developed a long-term relationship with ALPEK, they do not need an intermediary entity. Thus, the researcher decided not to represent this intermediary between the relationship of ALPEK and the cooperative in the network.

Nevertheless, there is a need to have an intermediary entity between the local cooperatives and the public funding because the local cooperatives by themselves also do not have the means to get funds from the public funding. Therefore, the intermediary asks to public funding for money to invest in 3D printing technology and services. The public funding funds the intermediary entity and the local cooperatives in exchange.

Identification of the value flows.

The next step is to identify the value flows of the network. A value flow exists between two stakeholders when one controls an important resource over another. In Fig. 3, the direct and indirect value flows (exchanged between the direct and indirect partners, respectively) are represented with filled and dashed arrows. For assessing each of the value flows within this additive symbiotic network, part I from questionnaire B and unstructured interviews with the expert from the focal organization were used.

Each value flow is constituted by a two-way relationship – the direct and the reciprocal flows. The reciprocal flows represent the inverse relationship of the direct ones. In scenario I, the eleven main value flows presented in Fig. 2 were identified within this network. The direct flows are represented with filled dashes, and the indirect flows are represented with arrowed dashes.

Thus, for scenario I, direct flows were identified as follows:

- **Flow 1** – INTI was responsible for conducting the necessary research, tests, and reports to study the feasibility of using PCR PET pellets to produce the recycled filament in 3D printers.
- **Flow 2** – The focal organization, B-PET, receives funding from Enyetech to develop projects since B-PET is an Enyetech spin-off company.
- **Flow 3 –** It is required by law to have approval from ANMAT for a company to sell food-grade PCR PET pellets. ALPEK is one of three recyclers' entities in Argentina with the ANMAT's necessary approval.
- **Flow 4** – In this additive symbiotic network, there is a need to have an Intermediary entity responsible for obtaining funds for the local Cooperative to invest in 3D printing technologies and services. This Intermediary entity creates a funding network that helps the Cooperative develop its businesses.
- **Flow 5** – After receiving the request from the Cooperative to create a funding network, the Intermediary proceeds to a project presentation for the funding entity.
- **Flow 6** – The focal organization provides the local Cooperative the 3D printing technology and essential consulting services to produce 3D printing consumables.
- **Flow 7** – This flow is composed of two separate flows:
- **Flow 7a** – After collecting the bales of PCR PET bottles, the local Cooperative sends them to ALEPK to be converted into PET pellets or flakes.
- **Flow 7b** – Since converting the waste streams into PET pellets or flakes requires additional processes to capture value from such waste streams, the local Cooperative additionally sends money to ALPEK.
- **Flow 8** – After producing the recycled filament, the Cooperative can use it for its own activities (prosumer) or sell it to its customers.
- **Flow 9** – The Cooperative can similarly sell the recycled filament to 3D printing services companies.
- **Flow 10** – After receiving the recycled filament, the 3D Printing Services companies use it to personalise and customize products and services for their Customers.

Intrinsic to all the direct value flows are the reciprocal flows that were identified as follows:

- **Reciprocal flow 1** – The Enyetech company gives INTI money to develop their research.
- **Reciprocal flow 2** - Considering that B-PET main's equity belongs to Enyetech, Enyetech receives money from B-PET.

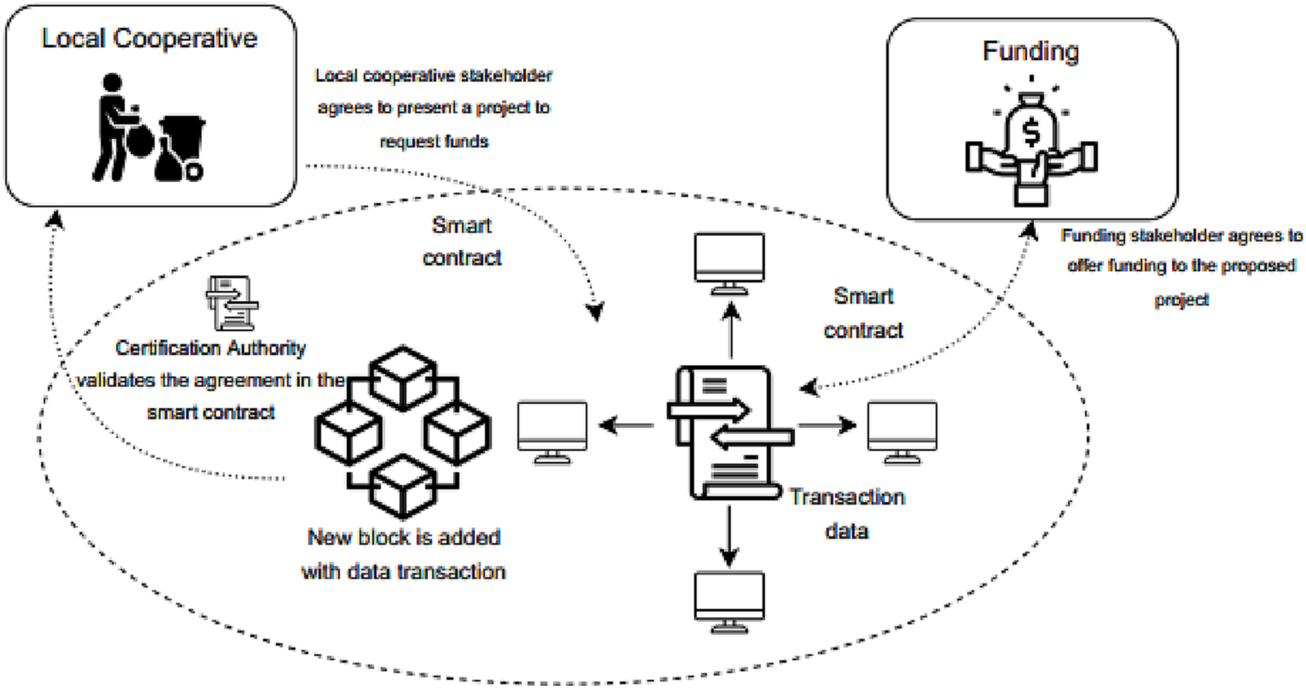

Fig. 5. Visual representation of how blockchain technology can be applied in an additive symbiotic network with a smart contract between a Local Cooperative and a Funding stakeholders.

- **Reciprocal flow 3** - In exchange for the approval to sell food-grade PCR PET pellets, ALPEK must pay a fee to ANMAT.
- **Reciprocal flow 4** - In exchange for creating a funding network, the Cooperative shares the funds with the Intermediary entity that helps them achieve the funding networks.
- **Reciprocal flow 5** - After evaluating the projects presented by the Intermediary entities, the funds are made available by the Funding stakeholder and delivered to each stakeholder (Intermediary and the Cooperative).
- **Reciprocal flow 6** - A licence fee is paid from the cooperative to the focal organization, B-PET, in exchange for the 3D printing technologies and services.
- **Reciprocal flow 7a** - ALPEK gives money to the local Cooperative in exchange for the bales of PCR PET bottles.
- **Reciprocal flow 7b** - PCR PET pellets or flakes are given by ALPEK to the local Cooperative.
- **Reciprocal flow 8** – The Cooperative customers give money in exchange for the 3D printing filament if the cooperative does not use it on its own.
- **Reciprocal flow 9** – The 3D printing services companies give money to the local cooperatives in exchange for the 3D printing filament.
- **Reciprocal flow 10** - The Final Consumers give money to the 3D Printing Services companies in exchange for customized products and services.

3.2.2. *Quantification of value flows – Value flow matrix*

To quantify each value flow previously identified, two criteria were used: the “urgency” and the “dependence” criteria characterized by Ferreira et al. (2019). The scores attributed to each value flow (both direct and reciprocal) are available in Appendix B. An aggregated value score results from the combination of these two criteria that aims to understand the power distribution among the stakeholders that participate in the symbiotic network, i.e., the stakeholders’ desire to be involved in the exchanges. An explanation of how to assign the correct aggregated value for each value flow within the network is given, and it is available in Appendix B. Since the score of each value flow is subjective to personal judgment, the main goal was to understand if a stakeholder’s preference was considered. Primary data collected from part II of questionnaire B were used.

The different aggregated scores that quantify each value flow allow to create a value flow matrix (Table 6) where the different flows exchanged among the stakeholders of an additive symbiotic network are characterized. Each cell contains the designation of the specific flow exchanged from the stakeholder in the row to the stakeholder in the column in the value flow matrix. Additionally, each cell has an aggregated score that quantifies the respective value flow and the resources exchanged in those flows.

The value flow matrix allows us to conclude about the power of the stakeholders involved in this symbiotic network for the first scenario. Different aggregated scores indicate that there is a power distribution among the stakeholders. The value flows with the highest aggregated scores are exchanged between the stakeholders who hold the most power in the network. In the case of this specific additive symbiotic network, the stakeholders Enyetech, B-PET, Cooperative Correcaminos, ALPEK, the 3D Printing Services companies and their Final Consumers are the stakeholders that hold the most power within the network.

3.3. *Mapping the value network of the case study – Scenario II – “to-be”*

To explore and understand the possibilities for adopting blockchain technology within the supply chain of the additive symbiotic network, unstructured interviews were taken with the expert of the focal organization. The possibilities to use blockchain technology are:

To identify players within the network and validate newcomers as a means to start introducing waste pickers to digital identities and the digital economy.

The smart contracts to support the resource exchanges between stakeholders in a symbiotic network could help visualize indicators such as Life Cycle Assessment or CO_2 footprint. These incorruptible records could help build end consumers’ confidence regarding sustainable practices, thus avoiding greenwashing and gaining sustainability certifications from independent entities.

It could be used as a tool to certify the stakeholders’ sustainability value to a supply chain through, for example, smart contracts that can

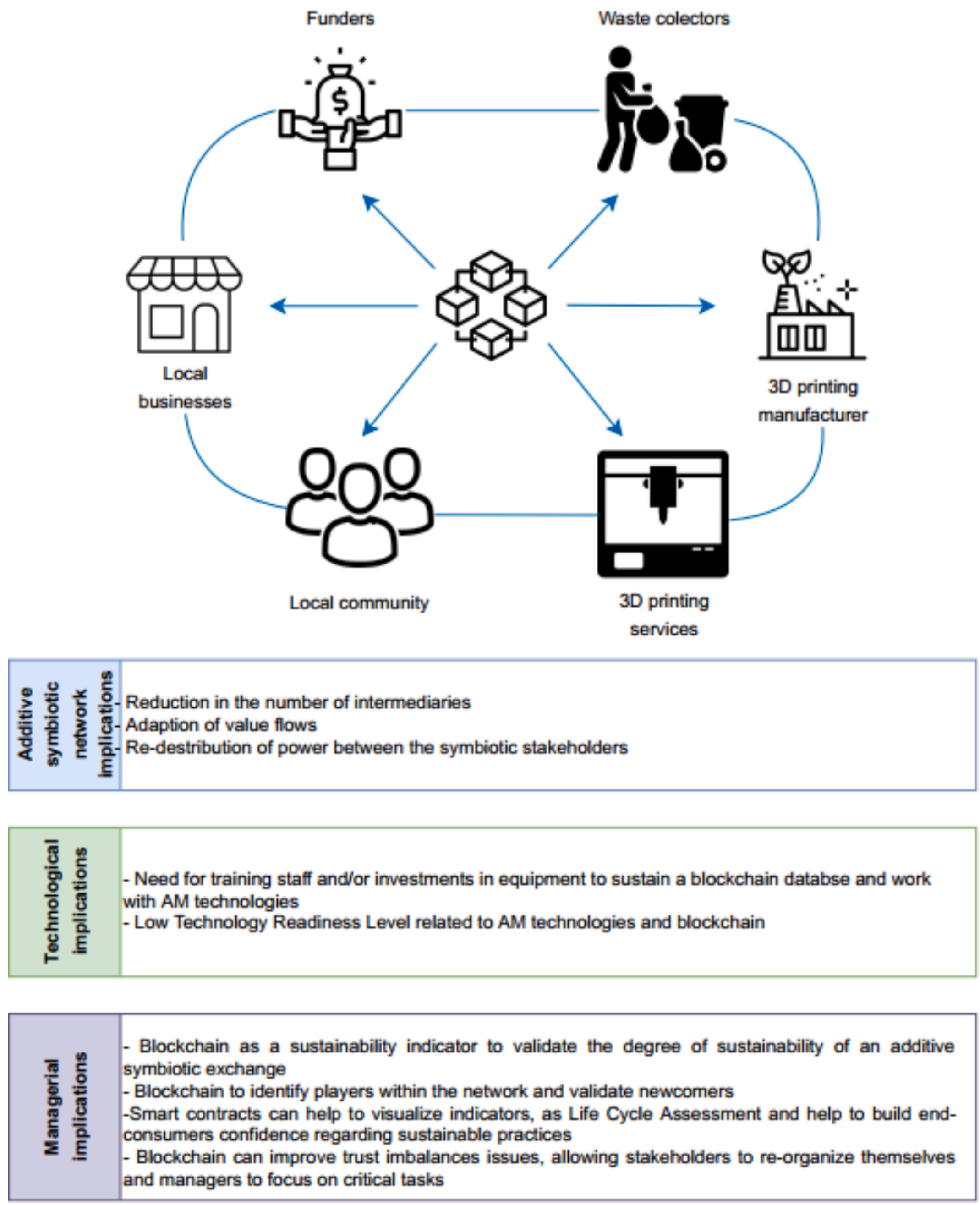

Fig. 6. Key implications of the adoption of blockchain technology in an additive symbiotic network.

deliver tokenized key indicators.

It could be used to automate the supply chain's contracts in the symbiotic network, consequently reducing the need to have intermediary entities.

End consumers and external stakeholders of the symbiotic network could have access, through blockchain technology, to sustainability indicators of the network, increasing transparency and value to society.

Considering the scope of this research work and the framework (Fig. 2) presented in section 2.3, the blockchain technology application that is related to the supply chain structure was selected: it can be used to automate the supply chain's contracts in the symbiotic network, consequently, reducing the need of having intermediaries' entities and the overall transactions costs. Thus, scenario II was analysed considering these four supply chain managements areas identified by Cole et al. (2019), where the adoption of blockchain technology is expected to bring value: i) to improve and automate contracts, ii) to reduce the need to develop trustworthy supply chain relationships, iii) to reduce the need of intermediaries and iv) to reduce the overall transactions costs. Scenario II was developed considering scenario I as the baseline. A newer mapping of the symbiotic network with the adoption of blockchain technology was developed (Fig. 4).

Scenario II considers that with the adoption of the blockchain technology in this additive symbiotic network, contracts within the supply chain are improved and automated, and thus, there is an exclusion of the Intermediary stakeholder between the Public Funding and the Cooperative, as well as the respective flows exchanged between them. In this new configuration, the Cooperative directly asks the Funding stakeholder for the necessary financial resources to invest in 3D printing technologies and equipment. Reciprocally, the Cooperative shares a fee from its profits with the Funding stakeholder. The remaining stakeholders and the flows (both direct and indirect) and the resources exchanged between them are kept similar to those identified and described in scenario I. The expert from the focal organization validated this potential new scenario as one of the possibilities for blockchain technology adoption.

For mapping and analysing the additive symbiotic network in this scenario II the same method used in subsection 3.1 was applied. A new value flow matrix (Table 7) was created and validated with the expert from the focal organization. Primary data from Questionnaire C and an unstructured interview were used.

4. Results and discussion

The results from the case study show the potential of blockchain technology regarding the development of additive symbiotic networks, fostering and improving the creation of industrial symbiosis networks in different contexts, as already highlighted by Ponis (2021) and Gonçalves et al. (2022). However, the results also show that the adoption of blockchain technology has different implications within the supply chain of an additive symbiotic network, highlighting how the role of innovative technologies, mainly associated with Industry 4.0, are contributing to provoke substantial disruptions in the supply chain management field (Queiroz et al., 2019).

From the value flow matrix created in scenario II (Table 7), we can characterize the value flows and the stakeholders with the highest power after adopting blockchain technology in an additive symbiotic network. On the one hand, even though blockchain technology adoption enhances the relationship between the Cooperative and the Funding stakeholders, it also increases the "urgency" and "dependence" criteria used to quantify each value flow. The Cooperative has a higher urgency in receiving the necessary funds to invest in 3D printing equipment and technologies and is also very dependent on the Funding stakeholder to receive those funds. However, the Funding stakeholder's "urgency" will depend on what is established in the smart contract (in terms of fees and long-term payments). Furthermore, the "dependence" of the Funding stakeholder is only related to the trust that the smart contracts will bring to the exchange with the Cooperative, which may lead the Funding stakeholder to incur in other similar networks (or similar projects). This validates the findings from Treiblmaier (2018) and Queiroz & Fosso Wamba (2019), showing that blockchain technology, specifically smart contracts, enables trusted information flows between companies that were disconnected before, altering the importance of inter-organizational relationships and, thus, affecting some of the value flows and stakeholders that engage in an additive symbiotic network.

Table 7 shows that most of the stakeholders previously identified in scenario I as having the highest power are the same after adopting blockchain technology. In scenario II, with the elimination of the Intermediary stakeholder from the network, the Funding stakeholder gained more power and, thus, became one of the stakeholders that hold the most power within this additive symbiotic network. This confirms Queiroz et al. (2019), that highlighted that blockchain technology is associated with the disintermediation of transactions, and this feature implies impacts on the supply chain of a network which involve aspects such as collaboration, trust and stakeholders relationships.

Several authors, such as Patala et al. (2020) and Henriques et al. (2022), have identified determinant factors for the emerging process of industrial symbiosis networks that include intermediaries. According to Yeo et al. (2019) and Patala et al. (2020), these intermediaries may be seen as industrial symbiosis facilitators that can perform different functions in order to accelerate new innovations for the reuse of materials and play a critical role in trust creation between previously unknown stakeholders. However, even though an intermediary is often needed in an industrial symbiosis setting, the results from the case study show that through the adoption of blockchain technology, there is a reduction in the number of intermediary stakeholders involved, corroborating the findings from Cole et al. (2019). This can be explained by the reliability concerning blockchain technology that allows through the use of immutable and decentralized ledgers to improve trust, transparency and security between the symbiotic stakeholders, discarding intermediaries from transactions and supporting authors such as Kouhizadeh et al. (2019), Patala et al. (2020) and Brookbanks & Parry (2022). Additionally, in scenario II, flow 4 (Fig. 4) replaces both flows 4 and 5 from scenario I (Fig. 3), allowing the Cooperative to directly ask for funds from the Funding stakeholder, which supports the findings from Treiblmaier (2018) that highlighted that there is a mutual adaption of the relationships in the supply chain with the adoption of the blockchain technology.

As the literature suggests, many studies are already offering tools to promote the development of industrial symbiosis (Lawal et al., 2021). Different phases of the industrial symbiosis process require different tools. General purpose tools can be used in an industrial symbiosis context to foster industrial symbiosis networks and, furthermore, tools such as CRIPS/NISP (Yeo et al., 2019) or SymbioSyS (Álvarez & Ruiz-Puente, 2017) are described as means to facilitate the development of industrial symbiosis networks among companies with none previously relationship established. However, trust is one of the most prominent challenges in the literature concerning industrial symbiosis networks (Ponis, 2021), and the current tools offered by the literature may have some limitations regarding the availability and disposal of data between stakeholders, which may comprise their relationships. Due to its characteristics, blockchain technology increases trust and guarantees transparency over an industrial symbiosis network. As industrial symbiosis facilitators or intermediaries are needed to sustain the network, it is expected that with the adoption of blockchain technology, these entities are no longer needed to effectively maintain an industrial symbiosis network. Fig. 5 shows a visual representation of how blockchain technology can work between stakeholders that participate in an industrial symbiosis network, using stakeholders that compose the additive symbiotic network under study. For this example, the Cooperative and Funding stakeholders were chosen because not only these stakeholders exchange money but also, they exchange information. Thus, Cooperative agrees to present a project to request for funds to invest in 3D printing equipment and services and initiates the process in the database. The Funding stakeholder may or not agrees to offer funding to the proposed project. If willing to offer funds, the Funding stakeholder offers an amount and creates a request. If the accepted by the Cooperative, a smart contract is created, validated by a Certification Authority and a new block is added with the transaction data.

From the comparison of both scenarios developed for the case under study, this research highlights some theoretical and practical implications of adopting blockchain technology in the supply chain structure of an additive symbiotic network. From a theoretical perspective, the adoption of such innovative technology promotes the development of additive symbiotic networks, offering a solution that supports the transactions occurring in the network, promotes ease of collaboration between stakeholders (allowing more direct relationships between them) and thus, offering a time-saving solution, as there is no longer need for intermediary stakeholders, or industrial symbiosis facilitators to verify all the exchanges and transactions within the network. However, it is expected that technological and managerial implications arise by adopting such disruptive technology. On the one hand, technological implications may relate to:

The need for training staff and/or equipment investments to sustain a blockchain database and work with AM technologies. For making the best use of new technologies, like AM and blockchain, all the stakeholders need to understand what the purpose is of using these technologies, how to implement them and their credibility (in the case of blockchain technology, stakeholders need to have confidence in an entity that is responsible for certificating and validating all the transactions in a network).

The low degree of digital literacy and technology of some of the stakeholders involved in the network. With the adoption of blockchain technology in this type of additive symbiotic network, waste-pickers are being introduced to digital entities and a digital economy, sometimes with no previous background or knowledge of the technology itself.

On the other hand, managerial implications can include, for instance:

The use of blockchain technology as a sustainability indicator or as a tool to validate the degree of sustainability of an additive symbiotic exchange (for example, having a smart contract between two stakeholders delivering a key performance indicator for that exchange).

Blockchain can be used to identify players within the network and validate newcomers (new cooperatives, new prosumers or new organizations that use AM technology to valorise plastic and or types of waste) as a means to start introducing waste pickers to digital identities (all the information and a unique identifier is used for each waste picker to detect them and their devices) and the digital economy.

The smart contracts that support the exchanges of resources (monetary, material and informational/knowledge) between stakeholders in a symbiotic network can help to visualize indicators such as Life Cycle Assessment or CO2 footprint. These incorruptible records could help build end-consumers confidence regarding sustainable practices, thus avoiding greenwashing and gaining sustainability certifications from independent entities.

Blockchain technology can be used to improve trust imbalances issues between the stakeholders in a symbiotic network, allowing them to organize themselves differently and permitting managers to focus on more critical tasks.

From a practical perspective, adopting blockchain technology may have several implications for the supply chain structure of an additive symbiotic network. Specifically, with the adoption of blockchain technology, there is a potential reduction in the number of Intermediary stakeholders involved in the network, and there is an adaptation of the current value flows within the network. These implications are manifested in the strength of the relationships between the stakeholders involved in an additive symbiotic network. Conclusions on the strength of the relationships can be retrieved by comparing the differences in the aggregated scores retrieved from the value flows matrixes created for both scenarios. In the scenario considering the blockchain's technology adoption (scenario II), the aggregated score for the value flows exchanged between the Cooperative Correcaminos and Funding stakeholders increases. This consequently affects the power distribution between all the stakeholders involved in the network, as with the adoption of blockchain technology, some new direct relationships may emerge, and with these, the power of some of the stakeholders involved may rise – there is a re-distribution of power between the network's stakeholders. By reducing the need for third-party entities and increasing trust between the stakeholders, it is expected that with blockchain technology, the stakeholders that participate in the most critical exchanges of an additive symbiotic network become more powerful since they exchange the essential resources to sustain the network.

In this sense, this research highlights that even blockchain technology can be a solution to promote the development of additive symbiotic networks, allowing to reduce its inherent supply chain's complexity, implications related to the power distribution among the stakeholders involved may arise. Fig. 6 summarises the main key implications of this research, considering an additive symbiotic network in which all the stakeholders are connected through a blockchain database, exchanging resources without third-party entities.

5. Conclusions

Blockchain technology has proven to have many potential benefits for enhancing circular economy initiatives, especially for developing additive symbiotic networks. However, adopting disruptive and innovative technologies such as the blockchain may have several implications within the supply chain structure of those additive symbiotic networks. The literature regarding the adoption of blockchain technology within the supply chain structure of an additive symbiotic network is still very scarce, and thus, this research intended to address this research gap. Considering a network theory lens, a case study representing an additive symbiotic network allowed to analyse two different scenarios: scenario I analysed the additive symbiotic network in its current state and a conceptual setting, i.e., scenario II, developed to understand the implications of the potential adoption of blockchain technology within the additive symbiotic network under study.

The development of both scenarios allowed the creation of two value flow matrixes that characterised the flows exchange among the stakeholders in the network before and after the potential adoption of blockchain technology. In scenario II, which considers the adoption of blockchain technology, the Intermediary stakeholder is excluded from the network, and consequently, there is an alteration of the value flows within the network. By comparing the two value flow matrixes, results show an increase in some of the aggregated values that quantify the exchanges in the network, affecting the strength of the relationships between the stakeholders and hence, contributing to a re-distribution of the power within the network's stakeholders. Specifically, in the scenario that considers adopting blockchain technology, a new stakeholder arises as holding the most power within the network. Thus, the adoption of blockchain technology is expected to have implications within the supply chain structure of an additive symbiotic network; explicitly, there is a re-distribution of the power within the networks' stakeholders with the adoption of blockchain technology.

Even though this research explored the adoption of blockchain technology in an additive symbiotic network, only the implications related to its inherent supply chain were analysed through a network theory lens that contemplates the relationships within the network. However, adopting blockchain technology can have other potential implications within the transactions that occur through the exchange of resources between symbiotic stakeholders. Thus, and as highlighted by Herczeg (2016), the three main transaction costs associated with the development of industrial symbiosis networks are: costs of negotiating the exchange terms, costs of enforcing and costs of partners' search. These costs can also be extended to the additive symbiotic networks' context. In this sense, future research venues that support the adoption of blockchain technology to enhance additive symbiotic networks considering a transaction cost theory lens, are needed. Another limitation of this research concerns the generalizability of results, considering that only a single case study was performed. However, generalizing the results was not the aim of this research. Instead, it aimed to encourage future studies to conduct a multiple case study approach to corroborate these results.

Moreover, future research is needed in what relates to the blockchain as a tool to enhance trust imbalances between the stakeholders of an additive symbiotic network, and it should include the development of blockchain-based architectures that support the implementation of these types of symbiotic networks, contributing to the literature regarding the adoption of the blockchain technology to enhance additive symbiotic networks.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clscn.2023.100095.

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